Chapter 5
Material and Weld Testing

5-1. Purpose of Testing

a. A structural inspection may reveal that certain structural members or connections are weakened due to some form of distress, but have not failed. With strength less than the design strength, these members and connections operate with a safety factor lower than that intended in design. The structure could continue to be operated with this reduced factor of safety, or the load conditions could be adjusted to raise the actual factor of safety. To determine the appropriate decision, engineering assessments that include fracture and fatigue analysis should be conducted, as discussed in Chapter 6. Mechanical properties of the structural members and welds are usually needed in the analysis.

b. For hydraulic steel structures fabricated in recent years, the materials used for the structural members and welds are usually well documented and can be identified from the design drawings. For older structures, however, information on mechanical properties of the structural materials or welds may not be readily available. Mechanical tests of these materials and welds are sometimes required to determine necessary information for fracture and fatigue analyses. In addition, determination of the chemical composition of unknown materials may be required.

5-2. Selection of Samples from Existing Structure

Material information that may be required to evaluate a steel structure includes chemical composition, tensile strength, bend ductility, fillet weld shear strength, hardness, and fracture toughness. The test samples may be taken from the materials left from original fabrication, removed from existing gate members or connections, or obtained from weldments made of similar materials with welding procedures similar to those used in the original fabrication.

5-3. Chemical Analysis

When the chemical composition of an existing structural (steel) material is not available, it may be necessary to perform a chemical analysis. This is an important initial task in the overall material and weld testing program. The information from this analysis will provide a basis for characterizing the properties of the unknown materials. This information can be used to assist in selecting appropriate NDT methods, assessing corrosion problems, conducting fracture analyses, and assessing material weldability for possible repair. A chemical analysis for material compositions should be in conformance with ASTM E30 and E350.

5-4. Tension Test

a. Tension tests provide information on the strength and ductility of materials under uniaxial tensile stress. The pertinent data obtained from a tension test are ultimate tensile strength, yield strength, Young's modulus, percent elongation, percent reduction of cross-sectional area, and the stress-strain relationship.

b. Transverse tension tests are generally used to determine weld quality during the weld qualification process. Similar tests could be used for existing structures if the original fabrication practices can be replicated. The transverse rectangular tension specimens are machined from a butt-welded plate, with the weld crossing in the midsection of the specimen (AWS B4.0 (AWS 1998a), Figure C-2). Specimens are then tested to failure in tension with results reflecting the effects of nonhomogeneous weld/metal interface and other weld defects. When weldment thickness is beyond the capacity of test equipment, the weldment is divided through its thickness into as many specimens as required to cover the full weld thickness. The results of the partial-thickness specimens are averaged to determine the properties of the full-thickness joint.

c. The base metal and weld metal tests are performed on a tensile testing machine in accordance with the requirements of ASTM E8. The machine should be calibrated in accordance with ASTM E4. The rate of straining should be between 0.05 and 0.5 units per unit of gauge length, per minute.

d. Material properties are calculated as follows:

(1) Ultimate tensile strength = maximum load/original cross-sectional area in the gauge length.

(2) Yield strength = load at 0.2 percent offset/original cross-sectional area in the gauge length.

(3) Percent elongation = (final gauge length - original gauge length)/original gauge length × 100.

(4) Reduction of area: Fit the ends of the fractured specimen together and measure the thickness and width at the minimum cross section. Calculate the reduced area.

e. At least two specimens should be tested for each sample type. The result of the tension test is the average of the results of the specimens.

5-5. Bend Test

a. In accordance with ASTM E190, bend tests are generally used in the weld qualification process for new fabrication. Similar tests, however, could be conducted for existing structures if original fabrication practices can be simulated. Guided bend tests are used to evaluate the ductility and soundness of welded joints and to detect incomplete fusion, cracking, delamination, effect of bead configuration, and macrodefects of welded joints. The quality of welds can be evaluated as a function of ductility to resist cracking during bending. The top and bottom surfaces of a welded plate are designated as the face and root surfaces, respectively. Face bends have the weld face on the tension side of the bent specimen, and the weld root is on the tension side for root bends. For thick plates, transverse slices are cut from the welded joint, and one of the cut side surfaces becomes the tension side of the bent specimen. For all types of bend tests, face, root, and side, the specimen is tested at ambient temperature, and deformation should occur between 1/2 and 2 min.

b. When the plate thickness is less than or equal to 10 mm (3/8 in.), two specimens are tested for face bend and two specimens are tested for root bend. When the thickness of the plate is greater than 10 mm (3/8 in.), four specimens are tested for side bend.

c. Transverse side bend test specimens (Figure A-5 of AWS 1998a) are used for plates that are too thick for face bend or root bend specimen. The weld is perpendicular to the longitudinal axis of the specimen. The side showing more significant discontinuities should be the tension surface of the specimen.

d. For a transverse face bend specimen (Figure A-6a of AWS 1998a), the weld is perpendicular to the longitudinal axis of the specimen. The weld face becomes the tension surface of the specimen during bending. For a transverse root bend specimen (Figure A-6b of AWS 1998a), the weld is perpendicular to the longitudinal axis of the specimen. The root surface of the weld becomes the tension surface of the specimen during bending.

e. During the test, the convex surface of the bent specimen should be examined frequently for cracks or other open defects. If a crack or open defect is present after bending, exceeding a specified size measured in any direction, the specimen is considered to be failed. Cracks occurring on the corners of the specimen during testing are not considered to fail a specimen unless they exceed a specified size or show evidence of defects (AWS 1998a).

5-6. Fillet Weld Shear Test

a. The fillet weld shear test is used to determine the shear strength of fillet welds. Fillet weld shear tests are generally used in the weld qualification process for new fabrication; however, similar tests could be conducted for existing structures if original fabrication practices can be simulated. The test is performed in accordance with the requirements of ASTM E8 on a tensile machine. The machine should be calibrated in accordance with ASTM E4. For longitudinal shear strength, the specimen is prepared in accordance with Figure E-1 of AWS B4 (AWS 1998a), and for transverse shear strength, the test specimen is prepared in accordance with Figure E-2 of AWS B4. The specimen is positioned in the testing machine so that the tensile load is applied parallel to the longitudinal axis of the specimen. The length, average throat dimension, and legs of each weld should be measured and reported. The welds are sheared under tensile loads and the maximum tensile loads are reported.

b. Shear strength in pounds per square inch is calculated by dividing the maximum load by the effective weld throat area (i.e., theoretical throat thickness times total length of fillet weld sheared). At least two specimens are tested. The result of the shear test is the average of the results of the specimens. A test is considered invalid if the failure is caused by a base metal defect. The fracture location must also be included in the report.

5-7. Hardness Test

a. Hardness tests are used to provide generic information on the material properties (primarily toughness and strength). Hardness measurements provide indications of metallurgical changes caused by welding, metallurgical variations, and abrupt microstructural discontinuities in weld joints, brittleness, and relative sensitivity to cracking under structural loads.

b. Specimens for hardness testing include as-welded partial or complete assemblies, weldments from which the reinforcement has been removed, and weld joint cross sections. For hardness tests of existing hydraulic steel structures, the weld reinforcement may or may not be removed. When it is removed, a local area of the reinforcement is ground smooth before testing. For large assemblies, portable hardness testers are available that can be transported for use in the field. Microhardness testing of welds is usually performed on ground, polished, or polished and etched transverse cross sections of the weld joints.

c. The most common hardness testing methods include Brinell, Rockwell, and Vickers tests. Selection of test method depends on hardness or strength of the material, the size of the welded joints, and the type of information desired. The Brinell, which is appropriate for field evaluations, produces a large indentation suited for large welds in heavy plates. The Rockwell test produces much smaller indentations than the Brinell test and is more suited for hardness traverses. The Rockwell hardness test is also suitable for field inspection if a portable tester is used (see ASTM E110). The Vickers test makes relatively small indentations and is suited for hardness measurements of the various regions in the weld heat-affected zone and for fine-scale traverses. The Brinell and Rockwell tests are generally used for hardness measurements of fusion-welded joints in laboratory or field environments. For each type of hardness test performed, at least five indentations should be made for each region. The result of the hardness test is the average of the indentations. The hardness values from different test methods can be correlated through a conversion chart provided by ASTM E140.

d. The Brinell hardness test is performed in accordance with the requirements of ASTM E10. It is an indentation hardness test using calibrated machines to force a hard ball into the surface of the material and to measure the diameter of the resulting impression after removal of the load. The Brinell hardness number, HB, is related to the applied load and to the surface area of the permanent impression made by a ball indenter.

e. The Rockwell hardness test is performed in accordance with the requirements of ASTM E18. This test is an indentation hardness test, in which a diamond spheroconical indenter or hard ball indenter is forced into the surface of the material in two operations. The Rockwell hardness number, HR, is a number derived from the net increase in the depth of indentation as the force is increased from a preliminary test force to a total test force and then returned to the preliminary test force. The higher the number, the harder the material.

f. The Vickers hardness test is performed in accordance with the requirements of ASTM E92. The Vickers hardness test is an indentation hardness test in which a square based pyramidal diamond indenter with specified face angles is forced into the surface of the material. The Vickers hardness number is related to the applied load and the surface area of the permanent impression.

5-8. Fracture Toughness Test

Fracture toughness testing provides a measure of resistance to fracture of a material. Test methods include Charpy V-notch test (CVN), Plane-Strain Fracture Toughness test (K_{Ic}), and Crack-Tip Opening Displacement (CTOD) test. The CVN test is used to measure the ability of a material to absorb energy. The K_{Ic} and CTOD tests are used to determine resistance to fracture given a specific crack subject to a specific stress level. As discussed in Chapter 2, the welding process and welding procedure have a significant effect on the fracture toughness of a welded joint. If possible, fracture toughness test specimens should be selected from a distressed member or connection, so that the test results are representative of the structure. As an alternative, test samples may be made using similar materials and welding procedures to those used in the original fabrication. Size and orientations of the test specimens taken from structure samples should follow the provisions specified in Figure D-3 of AWS (1998a). Test specimens should not contain metal that has been affected thermally as a result of cutting, preparation, or welding stops or starts. When an evaluation of the base metal or heat-affected zone is required, the location of the notch should be specified.

a. *Charpy V-notch test.*

(1) The CVN test provides information about behavior of metal when subjected to a single application of a load resulting in multiaxial stresses associated with a notch coupled with high rates of loading. For some materials and temperatures, impact tests on notched specimens have been found to predict the likelihood of brittle fracture better than tension tests or other tests used in material specifications.

(2) The specimen preparation and test procedure for the CVN test is described by ASTM E23. When specified, the surface finish of the V-notch of the Charpy impact specimen is 0.5 μm (20 μin.), or less. The testing machine is a pendulum type of rigid construction and of capacity more than sufficient to break the specimen in one blow. The test is performed at various specified temperatures over the range of temperatures that covers brittle to ductile behavior.

(3) Five specimens should be tested for each test condition, and the amount of energy absorbed by the specimen at fracture should be recorded. The highest and lowest values are discarded, and the result is taken as the average of the remaining three specimens tested. If any specimen fails to break, or jams in the machine, the data of that specimen are not included in the calculation of the average.

(4) In addition to the absorbed energy, other test indicators, such as lateral expansion of the fractured specimen and appearance of the fractured surfaces, can also be used to characterize the fracture toughness of the test material. The amount of expansion on each side of each half can be measured using a lateral expansion gauge. The two broken halves must be measured individually, and the larger value is used.

(5) Fracture characteristics of a material are also related to the appearance of the fractured surface. The fracture appearance can be quantified by measuring the length and width of the cleavage portion of the fracture surface or comparing the appearance of the fractured surface with a fracture appearance chart as shown in ASTM E23.

b. *Plane-strain fracture toughness test.* The critical stress intensity factor K_{Ic} characterizes fracture toughness of a material given the presence of a sharp crack when the state of stress at the crack tip is plane strain. K_{Ic} is a material property for a given temperature and load rate, and can be experimentally determined using compact tension test specimens or bend test specimens. The specimen preparation and test procedures must be in accordance with ASTM E399. For a result to be considered valid, it is required that both the specimen thickness and the crack length exceed 2.5 (K_{Ic}/σ_{ys}), where σ_{ys} is the 0.2 percent offset yield strength and K_{Ic} is the plane strain fracture toughness of the material at the desired test temperature and loading rate. The initial selection of a size of specimen may be based on an estimated value of K_{Ic} for the material to be tested. Due to practical considerations and cost considerations, CVN test results are easier to achieve and are more available than K_{Ic} test results. An approximation of K_{Ic} may be obtained through Barsom and Rolfe's (1987) two-stage CVN-K_{Ic} transition method as discussed in paragraph 7-1*b*.

c. *Crack-tip opening displacement test.* The CTOD test may be used to characterize the toughness of materials that are too ductile or lack sufficient size to be tested for K_{Ic}. CTOD is the displacement of the crack surfaces normal to the original (unloaded) crack plane at the tip of a crack. The CTOD at the fracture incipient load (critical CTOD) indicates the fracture toughness of the test material at a given temperature. The values of the critical CTOD can be used for inspection and fracture assessment criteria, when used in conjunction with fracture mechanics analyses. Preparation of the test specimen and the test procedure for CTOD testing are described in ASTM E1290.